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Modeling decadal timescale interactions between surface water and ground water in the central Everglades, Florida, USA

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Abstract

Surface-water and ground-water flow are coupled in the central Everglades, although the remoteness of this system has hindered many previous attempts to quantify interactions between surface water and ground water. We modeled flow through a 43,000 ha basin in the central Everglades called Water Conservation Area 2A. The purpose of the model was to quantify recharge and discharge in the basin's vast interior areas. The presence and distribution of tritium in ground water was the principal constraint on the modeling, based on measurements in 25 research wells ranging in depth from 2 to 37 m. In addition to average characteristics of surface-water flow, the model parameters included depth of the layer of 'interactive' ground water that is actively exchanged with surface water, average residence time of interactive ground water, and the associated recharge and discharge fluxes across the wetland ground surface. Results indicated that only a relatively thin (8 m) layer of the 60 m deep surfical aquifer actively exchanges surface water and ground water on a decadal timescale. The calculated storage depth of interactive ground water was 3.1 m after adjustment for the porosity of peat and sandy limestone. Modeling of the tritium data yielded an average residence time of 90 years in interactive ground water, with associated recharge and discharge fluxes equal to 0.01 cm d^{-1}. $^{3}H/^{3}He$ isotopic ratio measurements (which correct for effects of vertical mixing in the aquifer with deeper, tritium-dead water) were available from several wells, and these indicated an average residence time of 25 years, suggesting that residence time was overestimated using tritium measurements alone. Indeed, both residence time and storage depth would be expected to be overestimated due to vertical mixing. The estimate of recharge and discharge (0.01 cm d^{-1}) that resulted from tritium modeling therefore is still considered reliable, because the ratio of residence time and storage depth (used to calculated recharge and discharge) is much less sensitive to vertical mixing compared with residence time alone. We conclude that a small but potentially significant component of flow through the Everglades is recharged to the aquifer and stored there for years to decades before discharged back to surface water. Long-term storage of water and solutes in the ground-water system beneath the wetlands has implications for restoration of Everglades water quality.
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1. Introduction

Studies of interactions between surface water and ground water often target interactions that occur on

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timescales of days to months. For example, watershed hydrologists are typically interested in the relatively fast exchanges that occur, such as hillslope subsurface stormflow and bank storage of river channel water. These processes exert a major effect on the magnitude and timing of precipitation runoff from the watersheds and routing of that water through the channel network (National Research Council, 2002). Ecologists and biogeochemists have found reason to study even shorter timescale (minutes to hours) interactions between streams and the adjacent alluvial materials of the hyporheic zone that affect fate and transport of dissolved constituents, (Jones and Mulholland, 2000).

In a large wetland ecosystem such as the Everglades, there is considerable interest in both short and long timescales of surface-water and ground-water interactions. Short timescale interactions in the Everglades involve vertical exchange between wetland surface water and peat porewater (Krest and Harvey, 2003; Harvey et al., 2005), while longer timescale interactions between wetland surface water and the underlying sand and limestone aquifer also are of interest (e.g. Choi and Harvey, 2000; Bolster et al., 2001; Price et al., 2003; Wilcox et al., 2004). Previous investigations of interactions between surface water and shallow ground water in the Everglades were usually conducted near levees (Swayze, 1988; Meyers et al., 1993; Genereux and Slater, 1999; Bolster et al., 2001; Sonenshein, 2001; Nemeth and Solo-Gabriele, 2003). In general, interactions between surface water and ground water are much less well understood in the interior areas of the Everglades. For example, the effect that levees have in causing local increases in recharge and discharge within adjacent wetlands is generally confined to within a kilometer (Harvey et al., 2004). Municipal pumping wells appear to be important at greater distances (Wilcox et al., 2004), but in general there is comparatively little information about recharge and discharge in the vast areas of the Everglades interior.

Recent measurements of hydrogen and helium isotopes in ground water beneath the interior areas of the Everglades have provided new insights about interactions between surface water and ground water in these remote areas. For example, ground waters in the top 30 m of the Surficial aquifer in the southern Everglades have isotopically determined residence times that range from years to decades in the shallow aquifer, while ground water in the deeper parts of the aquifer are much older (beyond the detection range for these isotopes; Price et al., 2003). Recharge and discharge fluxes across the surface of the interior wetlands have recently been estimated by modeling vertical transport of naturally occurring, short-lived, radium isotopes in peat porewater (Krest and Harvey, 2003). Another method to determine recharge and discharge fluxes across the peat surface is measure the gradient in hydraulic head vertically through the peat and combine those data with bail test estimates of the hydraulic conductivity of peat as a means to compute recharge and discharge fluxes (Harvey et al., 2004). That approach indicated relatively high values of recharge and discharge (on the order of cm per day) that could not be explained by the effects of levees on ground-water flow. Other factors that could control recharge and discharge in the remote interior areas of the wetlands include seasonal and interannual variation in precipitation, as well as the effects of surface-water gravity waves created by pumping and spillway operations. For example, water releases through levee spillways cause the propagation of gravity waves toward interior areas of the wetland, which appear to drive alternating periods of discharge and recharge as they pass by locations in the interior wetlands (Harvey et al., 2004). Use of ground water geochemical tracers could further improve understanding of recharge and discharge in the Everglades. Improved models of surface-water and ground-water exchange are also needed as the basis for improved water quality models.

For the present study, concentrations of naturally occurring tritium were measured in ground water of Water Conservation Area 2A and used as the basis for quantifying long-term average recharge and discharge in the remote areas of the WCA-2A basin interior. The modeling of water and tracer flow was intentionally kept simple so that chemical sub-models could be easily added in the future to address water quality issues in the Everglades. A second objective was therefore to take a step towards evaluating whether the simple model of coupled surface-water and ground-water flow used here could be used in the future as a valid framework for modeling solute transport and reaction processes in the Everglades.

Tritium measurements came from 25 research wells in Water Conservation Area 2A that were screened at various levels in the Surficial aquifer. Measurements of $^3H/^3He$ were successful at a few of those wells, and those results offered an important check on ground-water residence times inferred from modeling tritium. The depth of the layer of Everglades ground water that exchanges with surface water was estimated directly from the distribution of tritium in ground water, while the more uncertain hydrologic parameters (average residence time of ground water and recharge and discharge fluxes) were estimated by adjustment to match the average tritium concentration in that layer. What is distinctive about the present study is that long-term average recharge and discharge fluxes were quantified in a remote interior area of the Everglades. Previous use of environmental tracers in Everglades ground water have either been in the vicinity of levees (e.g. Meyers et al., 1993; Wilcox et al., 2004), or when implemented in remote areas have generally stopped short of the goal of estimating recharge and discharge, instead reporting only the estimated residence time of ground water (e.g. Price et al., 2003).

2. Study area

The research was conducted in Water Conservation Area 2A (Fig. 1A), a large (42,525 ha) wetland basin in the central Everglades. Levee construction to enclose WCA-2A began in the 1950s, and the basin was completely enclosed by levees and canals by 1963 (Light and Dineen, 1994). Presently, WCA-2A shares boundaries with WCA-1 to the north and northeast, the Everglades Agricultural Area to the west and northwest, lands developed for light industry and residential areas to the east, WCA-2B to the south, and WCA-3A to the southwest (Fig. 1B). The following paragraphs provide a brief summary of aspects of hydrogeology and water management in the central Everglades that are necessary to interpret study results.

Surface-water flow in the Everglades has been extensively modified and is managed to control floods and accommodate water needs of a large and rapidly growing urban area to the east of the Everglades, as well as agricultural uses of water on the northwest side. What remains of the Everglades north of Everglades National Park have been compartmentalized into a series of very large artificial basins called Water Conservation Areas (WCAs) that are greater than 40,000 ha in area. The source of surface flow in the WCAs is from canals that drain from Lake Okeechobee and from the Everglades Agricultural Areas (EAA), from direct precipitation, and from ground-water discharge to the wetlands or to the canals that drain into the wetlands (Fig. 1). Surface-water flow passes from each conservation area to the next, moving southward through the wetlands, canals, culverts, and spillways until flow eventually reaches Florida Bay. Along the way, surface-water flow is augmented by precipitation and discharge from ground water, and depleted by evapotranspiration and by recharge to ground water. Due to the decreased water storage capacity of the altered wetland system, a large amount of surface water must occasionally be pumped eastward through canals to the Atlantic Ocean during periods of high water.

Although wetlands of the WCAs occasionally dry out, they normally have standing water at depths that typically range from 15 cm to 1.2 m. Beneath the surface water in WCA-2A is a layer of organic peat approximately 1 m thick that was formed from the incomplete decomposition of sawgrass, water lilies, and other emergent plants. The peat is fibrous with a low mineral or ash content, usually less than 10% (Gleason and Stone, 1994). The peat is in direct contact with the top of the Surficial aquifer that underlies the Everglades. In some areas, the peat is separated from the aquifer by a relatively thin layer of calcareous mud. In other areas, peat is in direct contact with a limestone layer or sand layer at the top of the Surficial aquifer.

The Surficial aquifer beneath the central Everglades is approximately 60 m thick in eastern Broward County (Fig. 1C) and is composed of layers of variable thickness of sand, shell, and limestone (Reese and Cunningham, 2000). The Surficial aquifer overlies an aquitard called the Hawthorn Formation that restricts hydrologic communication with the deeper Floridan aquifer. When averaged over the entire depth of the Surficial aquifer, hydraulic conductivity is relatively high in the coastal ridge to the east of the Everglades and declines to the west (Fish and Stewart, 1991). The marked decrease in

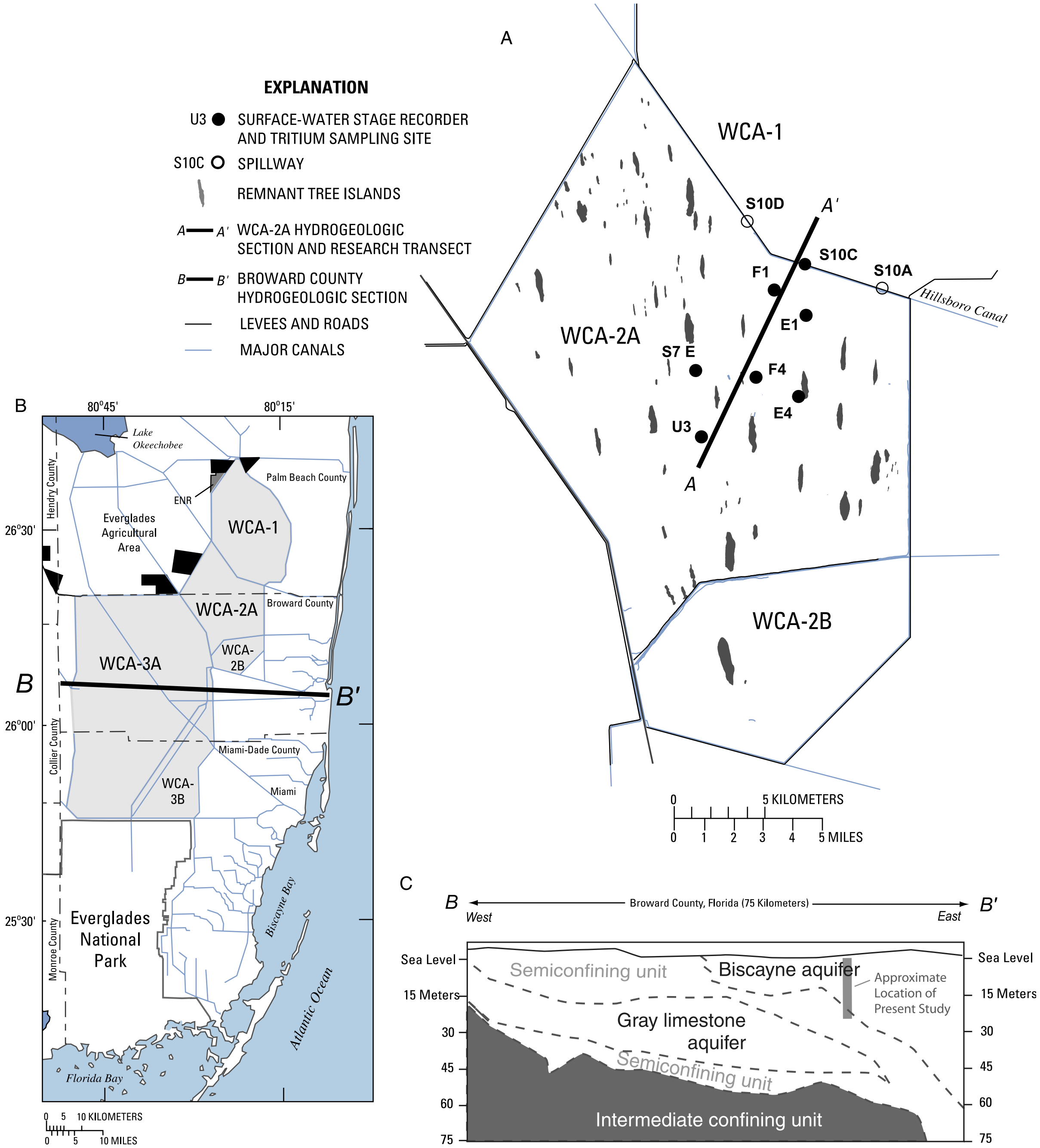

Fig. 1. Location of data collection sites in Water Conservation Area 2A (WCA-2A), central Everglades, south Florida (A). Location of WCA-2A within the larger Everglades system (B). Water Conservation areas are shown in light grey and location of a generalized hydrogeologic section labeled B–B′. Hydrogeologic cross-section shows the approximate location of the present study in relation to the Surficial aquifer system in southeast Florida (in white) and layering of two of its named aquifers (Biscayne and Gray limestone aquifers) and intervening semi-confining units (C). At the bottom boundary is a confining unit (shown in grey) that separates the Surficial aquifer from the deeper Floridan aquifer. Generalized hydrogeologic cross-section is from Reese and Cunningham (2000).

depth-averaged hydraulic conductivity from east to west in Palm Beach County accompanies the geological change from high porosity limestones and coarse sands in the east to limestones with variable degrees of cementation and finer sands in the western part of the Everglades (Miller, 1987; Harvey et al., 2002). In general, there is not as significant a decrease in hydraulic conductivity from east to west in the top 10 m of the Surficial aquifer (Harvey et al., 2002). The peat overlying the Surficial aquifer has a hydraulic conductivity that is approximately 2 orders of magnitude lower than the sand and limestone aquifer layers that lie beneath (approximately 30 cm d^{-1} compared with 2500 cm d^{-1}).

Fig. 2A illustrates the lithology along the research transect where tritium was sampled in ground water. The deepest wells extended a little more than half-way (∼35 m) into the Surficial aquifer, near the point of transition from the Fort Thompson formation in the Biscayne aquifer to the Tamiami formation, a semi-confining layer. At the top of the section is a 1-m layer of peat with undifferentiated freshwater marl and sand present just beneath it, and below that are layers of coarse sand (∼5 m thick), limestone with sand stringers (∼6-m thick), and sand transitioning to fines sand (∼21-m thick). More detailed data and interpretation of the lithology are available in Harvey et al. (2002).

3. Methods

The primary data needed for the present study were measurements of an environmental tracer in ground water that preserves information about ground-water residence time at various depths in ground water. Tritium is a naturally occurring, radioactive isotope of the hydrogen atom that decays by beta emission and has a half-life of 12.43 years. Prior to thermonuclear bomb testing, only the background level of tritium was present in the precipitation that recharged aquifers. Bomb testing in the mid and late 1950s and early 1960s increased tritium in precipitation to much higher levels (peaking in 1963) that 'labeled' ground water that was recharged at that time with relatively high tritium values. Now that more than 40 years has elapsed since bomb testing was stopped on a global scale, tritium in precipitation has declined to levels close to background again (IAEA/WMO, 2001). In order to distinguish relatively 'young' ground water (decades) from ground water that is much older (i.e. 'tritium-dead' ground water), it is particularly important to establish an accurate minimum detection limit for a given set of ground-water samples using a particular laboratory analysis. Even with the best available techniques for tritium analysis, there often remains considerable uncertainty about the age since recharge of a particular ground-water sample.

Improved dating of young ground water recently has developed through exploitation of the fact that radioactive decay of ^{3}H produces the noble gas helium-3 (^{3}He). Use of a measurement of tritogenic ^{3}He in addition to ^{3}H aids in defining what the initial input signature of tritium was to a ground-water sample, which has helped considerably in estimating the age of ground water following recharge in a number of aquifer types (Schlosser et al., 1988, 1989; Solomon et al., 1992). Price et al. (2003) used ^{3}H/^{3}He ratios to estimate that years to decades have elapsed since shallow ground waters in the Surficial aquifer of the southern Everglades were recharged. That study was one of the first investigations to estimate ground-water residence times in the Everglades using isotopes.

3.1. Measurement locations in Water Conservation Area 2A

Tritium was measured in ground water at seven wetland sites in WCA-2A (Fig. 1A). Six of the sites (F1, F4, E1, E4, U3, and S7-E) were located in the interior areas of the wetland. Research wells at each of the six interior sites had been emplaced in the underlying limestone and sand aquifer. Each site had 2–6 wells with depths ranging from 2 to 37 m below the ground surface. Site S10-C, with wells at three depths, differed from the other sites in the wetland interior by being located on the levee at the northern boundary of WCA-2A.

3.2. Well emplacement, ground-water sampling, and chemical analysis

Initial sets of exploratory shallow wells were drilled at five of the six interior sites in WCA-2A to depths of 2 and 8 m below ground surface by

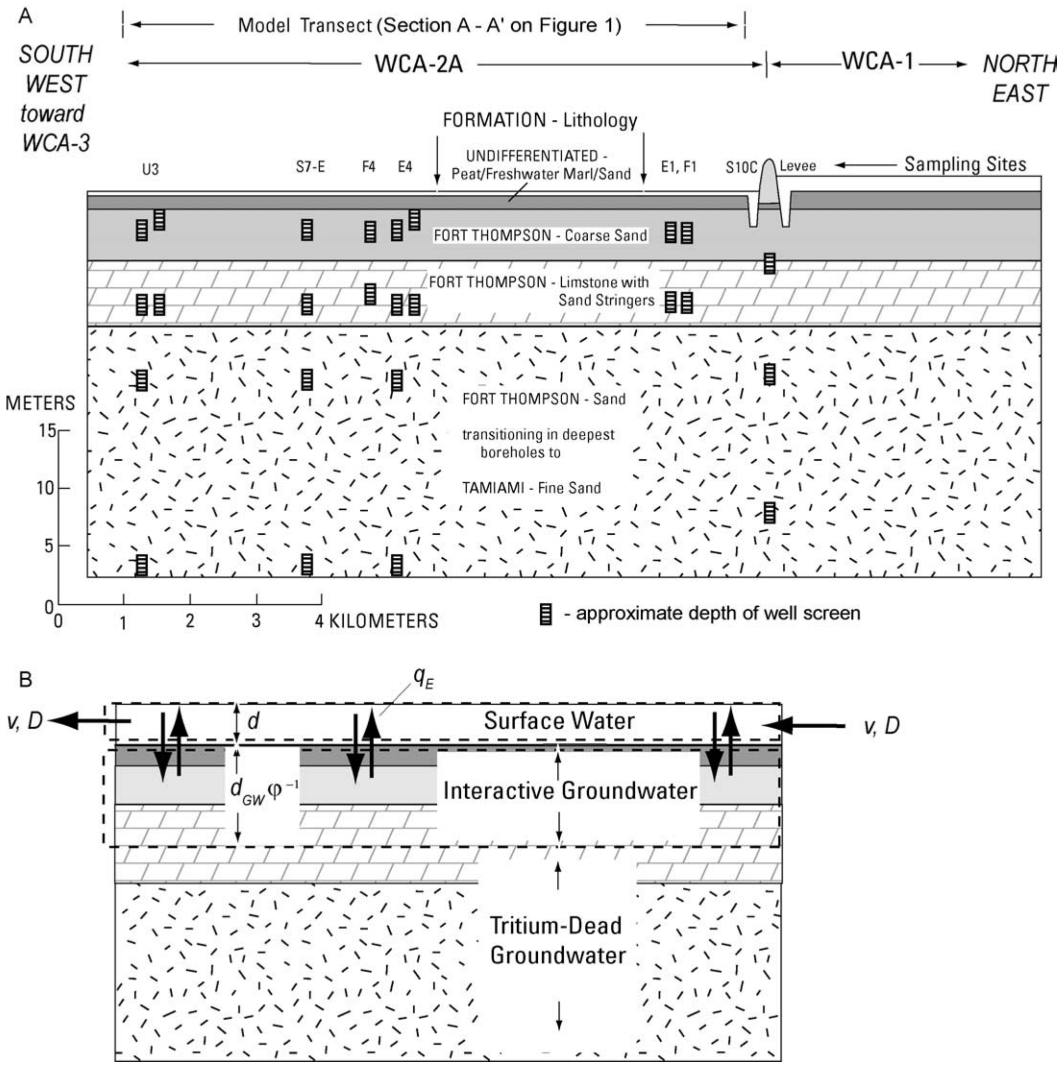

Fig. 2. Detailed hydrogeologic cross-section along research transect in Water Conservation Area 2A (section A–A′ shown in Fig. 1) where the model was applied (A), showing formation names and lithologic descriptions from Harvey et al. (2002). Conceptual model system showing one-dimensional transport of naturally occurring tritium tracer in surface water (B), where v equals the average surface-water velocity, d equals average surface-water depth, and D equals the longitudinal dispersion coefficient in surface water. Interaction between ground water and surface water is specified by a vertical exchange flux (q_E) that determines the rate at which surface water is exchanged for ground water in a well-mixed layer of the aquifer with thickness $d_{GW}\theta^{-1}$, where d_{GW} is the depth of water storage in the aquifer with detectable tritium, and θ is the aquifer porosity.

USGS-Geologic Discipline. A portable tripod drill rig with rotary coring capabilities (Shinn et al., 1984) was used to emplace those wells. Only surface water was used as the drilling fluid in that operation by pumping it down the annular space with hydraulic pumps. The depth of drilling under these conditions was limited by ‘running sands’ in the aquifer, the flow of which eventually equaled the flushing capacity of the pump and ended drilling. Upon completion of the borehole, a 3.8-cm (1.5-in. nominal) diameter PVC well with a 0.6-m long section of slotted (0.025-cm) screen at the bottom.

Additional boreholes were drilled at three wetland interior sites and one levee site using a more traditional mud-rotary method that was mounted conventionally on a truck trailer or on a specialized floating drilling barge. At sites in the wetland interior, two wells were emplaced in each borehole, resulting in one pair of shallow wells (4.5 and 9 m) and one pair of deeper wells (18 and 37 m) in addition to pre-existing wells emplaced at 2 and 8 m. Three boreholes were drilled at the S10C levee site (9, 18, and 27 m), and four wells were emplaced (4.5, 9, 18, and 37 m) at the new site in the wetland interior referred to as S7-E. The new wells were 5.1-cm (2-in. nominal) diameter PVC with a 0.6-m section of slotted (0.025-cm) screen at the bottom. Details of drilling, core recovery, logging, well construction, and development of the wells are given in Harvey et al. (2002). All told, 25 monitoring wells were emplaced between 1997 and 2000 in WCA-2A.

Before sampling ground water for chemical constituents, all wells were purged at rates ranging from 2 to 12 l min^{-1} until three well borehole volumes had been pumped, or longer if necessary for measurements of water quality parameters (temperature, pH, specific conductivity, oxidation–reduction potential, and dissolved oxygen) to stabilize in a flow cell attached to the discharge line. After purging, ground-water sampling began by pumping at a rate of approximately 1 l min^{-1} with a peristaltic pump through pre-cleaned 6-m sections of flexible tubing.

Unfiltered ground-water samples for tritium analysis were collected in 500 or 1000 ml glass bottles with polyseal caps from all wells on five sampling dates (September 1997, January 2000, April 2000, September 2000, and September 2001). Tritium samples were sent for analysis by the Tritium Laboratory at Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami. Tritium was measured at the RSMAS laboratory by internal gas proportional counting of H_2-gas followed by electrolytic enrichment and liquid scintillation counting. Accuracy of these low-level tritium measurements is approximately 0.1 TU (0.3 pCi per liter of ^3H_2O). The average standard deviation of replicate measurements reported by RSMAS for our samples was approximately 0.3 TU. For the present study, we used the sum of accuracy and average uncertainty (0.4 TU) as the best estimate of a tritium minimum detection limit (MDL). The MDL for tritium is important because it separates field measurements into two classes, those with greater than 0.4 TU have a high probability of containing relatively young ground water with measurable tritium while those with less than 0.4 TU have a dominant component of older, 'tritium-dead' ground water. Further details of tritium analysis and interpretation are available from the RSMAS Tritium Laboratory.

Several ground-water samples were collected for $^3H/^3He$ age-dating in September 1997. Those ground-water samples were sent for analysis of $^3H/^3He$ by the Lamont-Doherty Earth Observatory, New York. Details of sample collection, handling, and analysis are available from the USGS Reston Chlorofluorocarbon Laboratory. Samples were processed and interpreted with regard to ground-water age, i.e. time elapsed since recharge, by the contract laboratory. Although the results of $^3H/^3He$ analysis provided much more specific information about the residence time of the water sample in the aquifer, the collection of samples for measurement of $^3H/^3He$ ratios was potentially subject to more errors than collection for tritium alone. Samples with problems such as natural degassing processes in the aquifer or bubble capture in the sample were rejected and corrections were made for factors such as the input of terrigenic ^3He to the sample (Schlosser et al., 1998). For the present study, there were four useable results from a collection of ten samples that were analyzed for $^3H/^3He$ ratio.

3.3. Coupled model of surface-water and ground-water flow

The purpose of the tritium measurements and transport modeling was to estimate average (decadal timescale) recharge and discharge fluxes of water in the interior wetlands of WCA-2A. Tritium was generally only detectable in a shallow layer of fresh ground water near the top of the Surficial aquifer. The layer of ground water that is actively exchanged with surface water on a decadel timescale is referred to as 'interactive' ground water. It lies above a thicker layer of relict sea water in the lower part of the aquifer that dates from an earlier geologic period of higher sea level stand (Harvey et al., 2002). The model considers the depth of water storage and average residence time of ground-water layer in the 'interactive' layer of the aquifer, as well as several other parameters (tritium concentration in rainfall, and average water depth, velocity, and longitudinal dispersion in surface water). Average recharge and discharge fluxes over the 50-year simulation period are calculated from modeling results.

The USGS numerical code OTIS (*O*ne-dimensional *T*ransport with *I*nflow and *S*torage) (Runkel, 1998) was used for the tritium transport simulations. Although developed for streams, the OTIS code is general enough to be applied anywhere that surface-water transport characteristics are significantly affected by mass transfer into and out of storage reservoirs. For example, OTIS was recently used to simulate transport through waste water treatment wetlands in Florida (Martinez and Wise, 2003) and solute transport through wetlands of Everglades National Park (Harvey et al., 2005). For the present case, the model simulates transport and decay of tritium in surface water in WCA-2A and exchange of tritium with ground water that occurs as a result of recharge and discharge. Characteristics of long-term averaged average surface-water flow velocity and depth, along with measurements of the vertical distribution of tritium in an aquifer with known porosity, along with the well known decay rate of tritium, are the principal constraints that allow recharge and discharge to be determined.

Tritium transport was modeled along a 12-km transect of unit width that extends from the northern boundary of WCA-2A and WCA-1 (near site S10C) into the center of WCA-2A. The transect is roughly oriented parallel with the principal surface-water flow path which is towards the southwest in WCA-2A (Harvey et al., 2002). Fig. 2B illustrates the major components of the model schematically. The governing equations for the present study are presented below. Note that the variables of a typical application of the OTIS model in a stream (Runkel, 1998) are recast following a derivation that uses 'exchange flux' in the formulation of the mass transfer terms between surface-water and the storage zones (Harvey et al., 1996). The equations for stream and storage zone are as follows

$$\frac{\partial C}{\partial t} = -\frac{Q}{w\cdot d}\frac{\partial C}{\partial x} + \frac{1}{w\cdot d}\frac{\partial}{\partial x}\left(w\cdot d\cdot D\frac{\partial C}{\partial x}\right) + \frac{q_E}{w\cdot d}(C_{GW} - C) - \lambda\cdot C, \quad (1)$$

$$\frac{\partial C_{GW}}{\partial t} = \frac{q_E}{w\cdot d_{GW}}(C - C_{GW}) - \lambda\cdot C_{GW}, \quad (2)$$

where Q is the average volumetric flow rate of surface water through the wetland [$L^3\,t^{-1}$]; t is time [t]; x is distance [L]; C is the concentration of tritium [TU] in surface water; C_{GW} is the concentration of tritium [TU] in interactive ground water layer defined as the layer of shallow ground water that undergoes exchange with surface water due to alternating periods of recharge and discharge; D [$L^2\,t^{-1}$] is the longitudinal dispersion coefficient in surface water; w [L] is the width of the modeled cross-section in surface water and ground water; d [L] is the average depth of the surface water; d_{GW} [L] is the average depth of water storage in the layer of interactive ground water; λ [t^{-1}] is the first-order coefficient for radioactive decay of tritium in surface water and ground water ($1.8\times10^{-9}\,s^{-1}$ or 5.6% per year); and q_E [$L^2\,t^{-1}$] is the coefficient describing bi-directional exchange that occurs between surface water and ground water by vertical fluxes (recharge and discharge) across the ground surface. The units of exchange flux can be interpreted physically as a volume of water exchanged per unit time, per unit length along the model domain in the direction of surface-water flow.

Application of the model involves adjusting the parameters of the model to fit measured tritium data. Among the ground-water parameters, calibration is simplified because depth of ground water storage, d_{GW}, is independently specified from the tritium observations. Note that ground-water residence time is uniquely related to depth of water storage (multiplied by transect width) and divided by a water exchange flux

$$q_E = \frac{d_{GW}w}{t_{GW}}. \quad (3)$$

As a result, the residence time is the only ground-water parameter that need be adjusted to fit observed tritium data. Average recharge and discharge fluxes (in units of $L^3\,L^{-2}\,t^{-1}$ or simply $L\,t^{-1}$) are both estimated by dividing the exchange flux by the transect cross-sectional width, w, as shown

$$\text{recharge or discharge} = \frac{q_E}{w}. \quad (4)$$

Note that for the present model of flow through central WCA-2A that the flow system is wide enough that transport can be assumed to be invariant with small to moderate changes in width. A 'transect' model of unit width ($w=1$) is therefore appropriate, which results in estimates of recharge and discharge that are both equivalent to the water exchange flux, q_E.

3.4. Model initial and boundary conditions

The simulation started in 1953, just before significant bomb testing began and when tritium in precipitation was relatively low. The initial and boundary conditions that were needed include specification of an upstream boundary condition for tritium in surface water, and specification of the initial concentration of tritium throughout surface water and shallow interactive ground-water at the start of the simulation. In the mid-1950s, tritium levels increased substantially in precipitation worldwide due to the advent of nuclear bomb testing. Tritium peaked in precipitation in 1963 and has decreased slowly ever since. The upstream boundary condition for our simulation (tritium concentration in surface water at the upstream location where water inflow occurs to the wetland transect) was prescribed on the basis of estimates of tritium in precipitation at Miami, FL. The initial conditions for the simulation were determined by initializing all surface-water and ground-water concentrations with the tritium concentration in precipitation in 1953, and then following the procedure of Runkel (1998) by running the model until steady concentrations were achieved at all locations.

Tritium data were available for Miami from 1964 to 1991 and from 1996 to 2001 (IAEA/WMO, 2001). Because ground water with a decadal-scale residence time would not be expected to reflect the monthly variations in tritium concentrations that affect precipitation, the tritium data for precipitation were averaged annually (weighted by monthly precipitation) to smooth the data record. For years without tritium measurements in Miami, the values were calculated based on a linear regression approach using the longer record of measurements from Ottawa, Canada (IAEA, 1981). Tritium values used for the years 1963–1991 and 1996–2001 were the annual averaged of the monthly measured values in Miami (Fig. 3). Annual mean values shown in Fig. 2 for the years prior to 1963, and the years 1992–1994 were determined from a regression of Miami tritium on tritium data from Ottawa (log [Miami tritium] = 0.9826[Ottawa tritium] − 0.8920, $r^2=0.96$). Tritium was not measured in either city in 1995, so the 1995 tritium value for Miami was estimated by linear interpolation between estimates for 1994 and 1996 (value for 1995 shown in Fig. 3 as an x).

3.5. Model sensitivity analysis

Before applying the model to simulate the field data, a 'base' simulation was needed with rough, order-of-magnitude estimates of parameters, for the purpose of exploring model behavior and sensitivity. Results of sensitivity analyses would be important for testing assumptions of the model and guiding the final simulations to quantify recharge and discharge. An average surface-water velocity ($0.5\ \mathrm{cm\ s^{-1}}$) and depth of surface water (0.3 m) were selected to represent long-term average values for the base simulation (Harvey et al., 2002; Rybicki et al., 2002). A preliminary estimate of the depth of water storage in the interactive layer of the aquifer was based on observed depths of the layer of freshwater that overlies the much older relict seawater in the aquifer (Harvey et al., 2002). An initial estimate of exchange flux was calculated (using Eq. (3)) to be consistent with a modeled ground-water residence time on the order of decades. Table 1 contains the initial parameter estimates used in the base simulation for sensitivity analyses.

Sensitivity of the model results to individual parameters was tested by adjusting parameters of the base simulation one at a time by a factor of 2 and re-running the model. Fig. 4 shows an example of how tritium concentrations in ground water are affected by varying the exchange flux across the ground surface. Overall results of the sensitivity analysis are summarized in Table 2. The root mean squared error (RMSE) of tritium concentrations in the interactive ground-water zone was calculated for each new simulation with relation to the base simulation. The RMSE is a measure of the absolute difference in the base simulation and new simulation results caused by the parameter change. The results show that the modeled tritium concentrations in shallow interactive ground water were primarily sensitive to two parameters, d_{GW} and q_E (Table 2). The sensitivity to surface-water velocity and longitudinal dispersion in

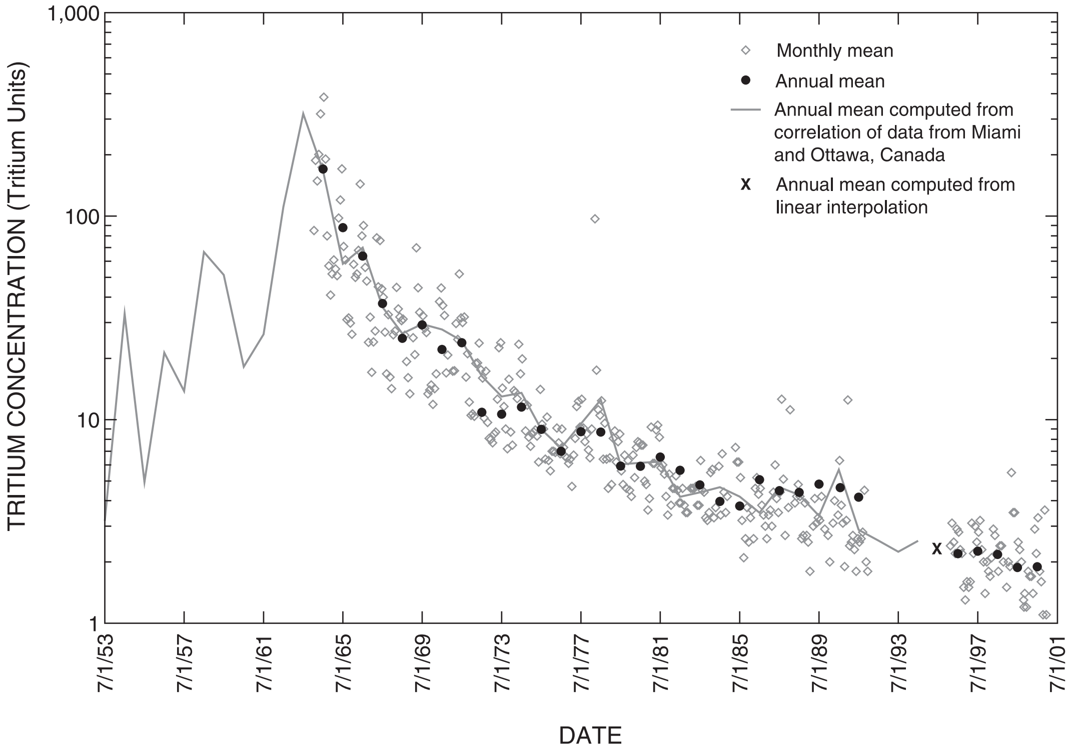

Fig. 3. Tritium in precipitation for Miami, Florida. Annual mean tritium values were computed directly from monthly measurements in Miami when available. When Miami tritium data were unavailable, tritium was computed from a linear regression of Miami tritium data (monthly weighted annual means) on similarly weighted tritium data from Ottawa, Canada.

surface water are minor in comparison. Since d_{GW} is constrained by the observations of tritium and since this parameter only appears in the model in ratio with q_E, only the model ground-water residence time ($t_{GW}=d_{GW}w/q_E$), needed be adjusted to achieve a final model fit to tritium data because all other parameters were either relatively insensitive (surface-water velocity v and longitudinal dispersion D), or fixed ($w=1$).

3.6. Justification for model simplifications

One of the most important model simplifications is that temporally and spatially averaged recharge must equal discharge. This simplification is reasonable if (1) temporal averaging is long enough that changes in water storage in the wetland are negligible, and (2) if all water that is recharged across the wetland ground surface is eventually discharged across the same surface. With regard to assumption (1), temporal averaging of the water balance in WCA-2A over decades is almost certainly long enough that changes in water storage in the wetland can be ignored. With regard to (2), there is thought to be a small 'net recharge' flux over the long-term in WCA-2A due to very slow transport to ground-water areas outside WCA-2A, but that flux is thought to be mainly important near the eastern boundary of WCA-2A and, when averaged over WCA-2A as a whole, the net flux is thought to represent only a small difference between

Table 1
Parameter estimates used in the base simulation

Parameter	Value
Surface-water velocity, v	0.5 cm s^{-1}
Depth of surface water, d	0.30 m
Longitudinal dispersion in surface water, D	0.01 $m^2\ s^{-1}$
Depth of shallow interactive ground water, d_{GW}	1.9 m
Water exchange flux across ground surface, q_E	0.2 cm d^{-1}
Tritium decay rate, λ	$1.8\times10^{-9}\ s^{-1}$

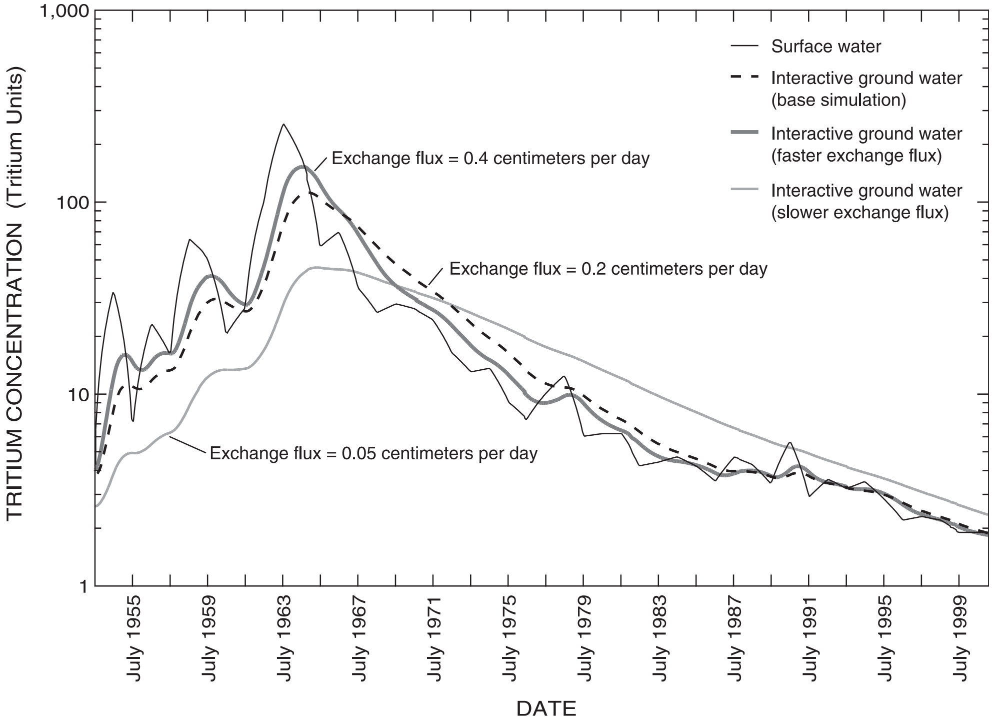

Fig. 4. Sensitivity of model to changes in the exchange flux between surface water and the layer of interactive ground water, q_E.

the much larger recharge and discharge fluxes across the wetland ground surface (Harvey et al., 2002).

Our use of a model that does not allow for horizontal flow in ground water also needs to be justified. Also needing justification is the decision to average parameters spatially along the transect even though the model allows for horizontal spatial variation in ground-water storage, residence time, and water exchange flux parameters. For example, the choice was to either account for horizontal spatial variation in parameters by implementing 'sub-reaches' within the model, each with different parameters. Or, if spatial variation is minimal or is random, reach-averaged values of the parameters could be determined for a single reach. The second choice was selected as being most reasonable for this model of surface-water and ground-water interactions in WCA-2A. Several considerations were important, including a consideration of the timescales of the various processes and the form of the spatial variability. Those considerations are summarized as follows: (1) horizontal ground-water velocities in WCA-2A ($\sim$0.02 cm d^{-1}) from Harvey et al. (2002) indicate that the residence time of horizontally flowing ground water in WCA-2A is on the order of hundreds of thousands of years, which is extremely

Table 2
Sensitivity of tritium concentrations in ground water to factor of 2 changes in the input parameters

Parameter	Root mean squared error (from base simulation)	
	Increase parameter	Decrease parameter
Depth of shallow interactive ground water, d_{GW}	236	235
Water exchange rate across ground surface, q_E	231	233
Surface-water velocity, v	3	6
Longitudinal dispersion of surface water, D	2.8×10^{-4}	1.4×10^{-4}

The root mean squared error (RMSE) was computed relative to the base simulation.

slow relative to the timescale of tritium decay (12.43 years), the residence time of surface water along the transect (approximately 30 days), and also the timescale of significant changes in the tritium concentration of precipitation (years); and (2) horizontal variation in the water exchange flux (based on variability of observed tritium profiles in ground water) do not appear to vary systematically along the transect.

We addressed the question of what is the appropriate level of simplification of our model by evaluating the sensitivity analysis results (Table 2) and also evaluating variability of tritium measurements. It appears safe to ignore the effects of horizontal ground-water flow based on the relative timescales of surface-water and ground-water flow, tritium variation in precipitation, and horizontal movement of ground water. Also due to the relative timescales of flow and tritium decay, no longitudinal gradient is expected to develop in surface-water tritium. These comparisons explain the insensitivity of the model to the average velocity and longitudinal dispersion coefficient in surface water (Table 2). The question of whether to represent longitudinal variability in ground-water parameters in sub-reaches, or simply average that variability in a single reach, rested on the evaluation of measured tritium profiles in ground water; these data are presented in the next section. It is sufficient to say here that the evaluation supported use of a one-reach model with (horizontally) spatially averaged parameters. It is important to note that the model's complexity could easily be expanded as needed for modeling other data sets.

Is further simplification of the model possible? Since the model is generally insensitive to average characteristics of surface-water flow and transport, and because spatial variation in the measured tritium profiles can be appropriately averaged, the problem of estimating recharge and discharge in the central Everglades potentially reduces even further to the simple calculation presented in Eq. (3). Use of Eq. (3) instead of the full model depends on having independent estimates of average ground-water residence time and depth of water storage in the interactive layer of the aquifer. This simple procedure to calculate recharge and discharge fluxes will be especially useful for data such as that presented by Price et al. (2003), where numerous independent estimates of ground-water residence time and depth of the interactive layer were determined by measurement of $^3H/^3He$ ratios in ground water in Everglades National Park. It should be emphasized that use of such a simple calculation as Eq. (3) to compute recharge and discharge in the Everglades is justified only because we demonstrated that tritium transport and decay in the interior areas of the Everglades are insensitive to rates of horizontal transport of ground water, as well as the insensitive to surface-water velocities and rates of longitudinal dispersion. Application in areas of the Everglades closer to its boundaries, or application with different tracers could invalidate use of Eq. (3).

4. Results

Tritium measurements from 25 wells at seven sites in WCA-2A are shown plotted as a function of depth in the aquifer in Fig. 5A. The data were temporally averaged because no clear temporal trends existed for samples collected over the 4-year sampling period. Based on the results of the sensitivity analysis, and on the examination of residence times of surface-water and ground-water flowing horizontally in WCA-2A relative to the half-life of tritium, horizontal transport of tritium both in surface water and ground water were expected to have minimal effects on vertical distribution of tritium in the aquifer. Therefore, tritium data from different locations in the wetland were combined by averaging spatially tritium values from similar vertical intervals of well-screen depth. Averaged data are shown in Fig. 5B. Tritium data for individual wells along with the spatially averaged tritium concentrations and standard deviations for four well-screen depth ranges (0–4.5, 4.5–9, 15–18, and 34–37 m) are shown in Fig. 5B. As explained earlier, tritium measurements beneath the S10C levee were not included in the spatial averages.

The first important observation about spatially averaged tritium data is that reliable detections of tritium (>0.4 TU) were almost entirely restricted to wells less than 8 m deep (Fig. 5B). Average ground-water tritium concentrations were 1.8 TU in the shallowest depth range (0–4.5 m), 0.63 TU in the next deepest depth range (4.5–9 m), and below the MDL in the two depth ranges in deeper ground

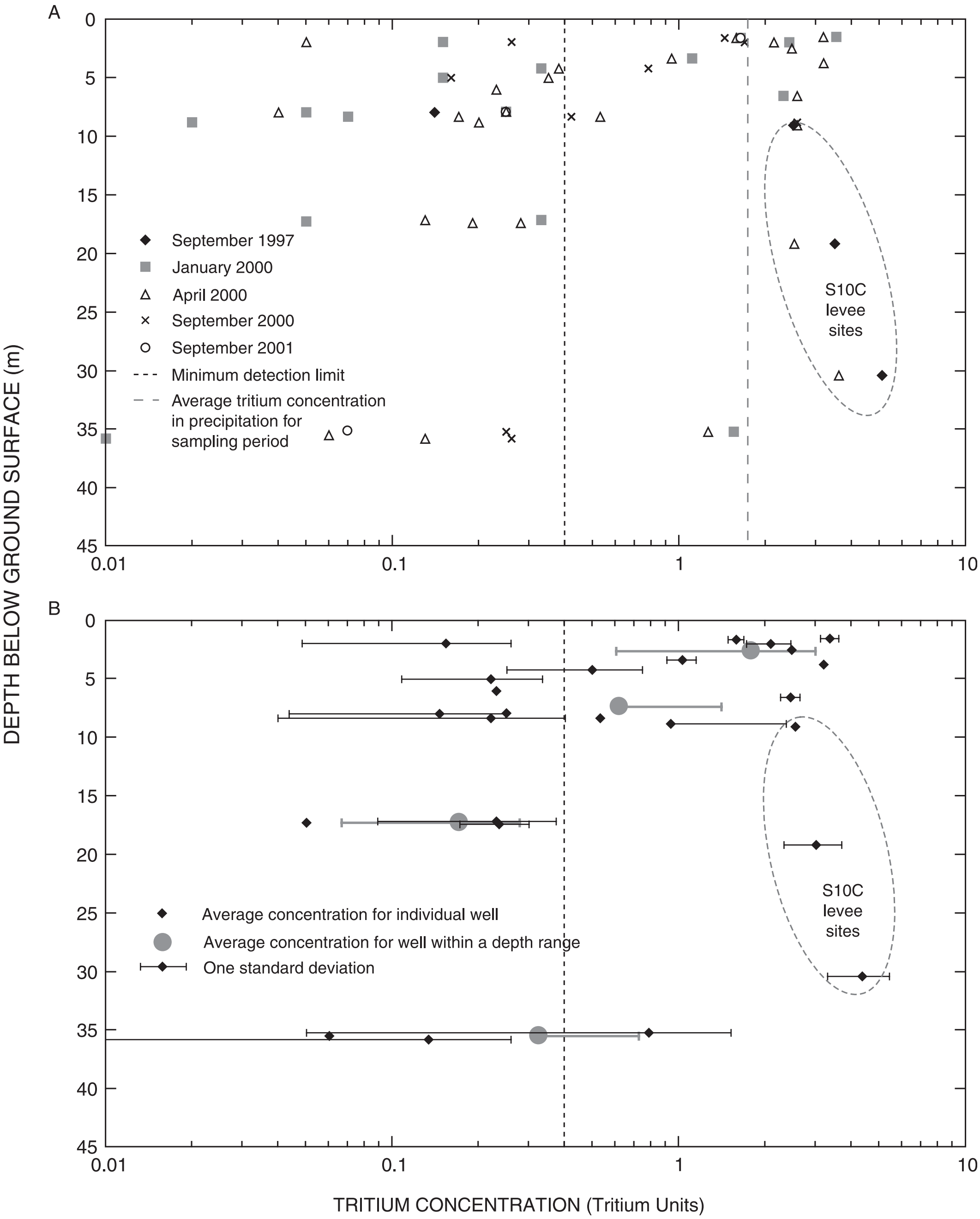

Fig. 5. Tritium data from the ground-water monitoring wells in Water Conservation Area 2A, south Florida, collected between September 1997 and September 2001 (A). Time-averaged tritium concentrations for each well (diamonds) are shown, along with spatially averaged tritium concentrations (larger grey circles) for the following depth ranges (0–4.5; 4.5–9, 15–18; and 34–37 m (B). Error bars represent one standard deviation of the spatial averages. The average concentration of tritium in precipitation for the sampling months was 1.8 TU (shown as long vertical dashes in (A)). Minimum detection level of tritium was 0.4 TU, shown as short vertical dashes in (A) and (B). After excluding data collected in wells beneath the levee, the layer of 'interactive' ground water was determined as the depth of detectable tritium in the aquifer based on the spatially averaged data in (B).

water (15–18 and 34–37 m) (Fig. 5B). Relatively high rates of ground-water flow beneath levees is a well studied phenomena (Swayze, 1988; Meyers et al., 1993; Genereux and Slater, 1999; Bolster et al., 2001; Sonenshein, 2001; Nemeth and Solo-Gabriele, 2003) that was also characterized locally in WCA-2A (Krest and Harvey, 2003; Harvey et al., 2004). Since the present goal was to quantify recharge and discharge in the interior areas of WCA-2A, tritium data beneath the levee were not used in modeling analysis. In an upcoming section we justify the assumption that horizontal flow of tritium in ground water from levee boundaries was not important to our analysis.

4.1. Estimating tritium concentration and water storage in interactive ground water

In order to determine the average tritium concentration throughout the top 8 m of interactive ground water, the depth-distribution of tritium and porosity must be taken into account. Tritium concentrations clearly decrease with increasing depth in the aquifer, but the exact form of the decline in tritium concentration is difficult to specify. The best method of depth averaging was presumed to be computing a depth and porosity-weighted average of tritium concentrations based on average tritium concentration at the midpoints of the two depth classes of wells. The shallow depth class ranged between 0 and 4.5 m with a midpoint of 2.25 m, and the deeper class ranged between 4.5 and 8 m with a midpoint of 6.75 m, respectively. The average concentration for each well class was assigned to all depths within the corresponding depth range. Furthermore, depths in the top 1 m (peat) of the aquifer were assigned a porosity of 0.98 to represent peat, while the layer between 1 and 8 m (sandy limestone) were assigned a porosity of 0.3 (Harvey et al., 2002). The total storage depth of water that resulted from those calculations was 3.1 m in the top 8 m of the aquifer. Approximately one-third of the water storage (0.98 m) was accounted for by water storage in peat. The resulting estimates of average tritium concentration in the 8-m layer of interactive ground water was 1.5 TU. It should be noted that this estimate of average tritium concentration is uncorrected for mixing that may have occurred with deeper, tritium-dead ground water. Vertical mixing between those waters would cause both residence time (t_{GW}) and the depth (d_{GW}) of the relatively young component of ground water to be overestimated. The reasons for overestimation are that upward transport of tritium-dead water dilutes the average tritium concentration of young ground water with tritium free water, leading to overestimation of residence time for the component of young ground water. At the same time, downward transport of young ground water with tritium increases the apparent depth of interactive ground water. The approach we chose was to proceed with the modeling and accept the possible overestimation of t_{GW} and the d_{GW}. Even if vertical mixing was later shown to be important, we relied on the fact that mixing would probably have little effect on estimates of recharge and discharge. That is because (1) the total mass of tritium in ground water remains unaffected by vertical mixing, (2) both residence time and depth are simultaneously overestimated if vertical mixing with tritium-dead water occurs, and (3) since water storage depth and residence time in the interactive ground-water layer appear in ratio in the calculation of exchange flux (Eq. (3)), it is probable that vertical mixing would have little or no overall effect on our estimate of exchange flux. A later evaluation of the effect of vertical mixing was made possible by comparison of model estimated residence times with residence times estimated using measurements of $^3H/^3He$ ratios in several wells. Significant vertical mixing with tritium-dead water would be evident in shorter residence times estimated from $^3H/^3He$ ratios compared with model-estimated residence times obtained by fitting to tritium data. The results of the residence time comparison and the resulting interpretation of the importance of vertical mixing are discussed later in this paper.

4.2. Determination of average recharge and discharge fluxes

Tritium transport was simulated using fixed values of surface-water velocity, surface-water depth, and longitudinal dispersion in surface water (values given in Table 2). Fig. 6 shows a range of simulation results using the following values of ground-water residence time, $t_{GW}=1$, 3, 10, 30, 100, 300, and 1000 years. Fig. 7 compares the results of those simulations with measurements of tritium in ground water categorized by well depth class. Although, there is wide variation in

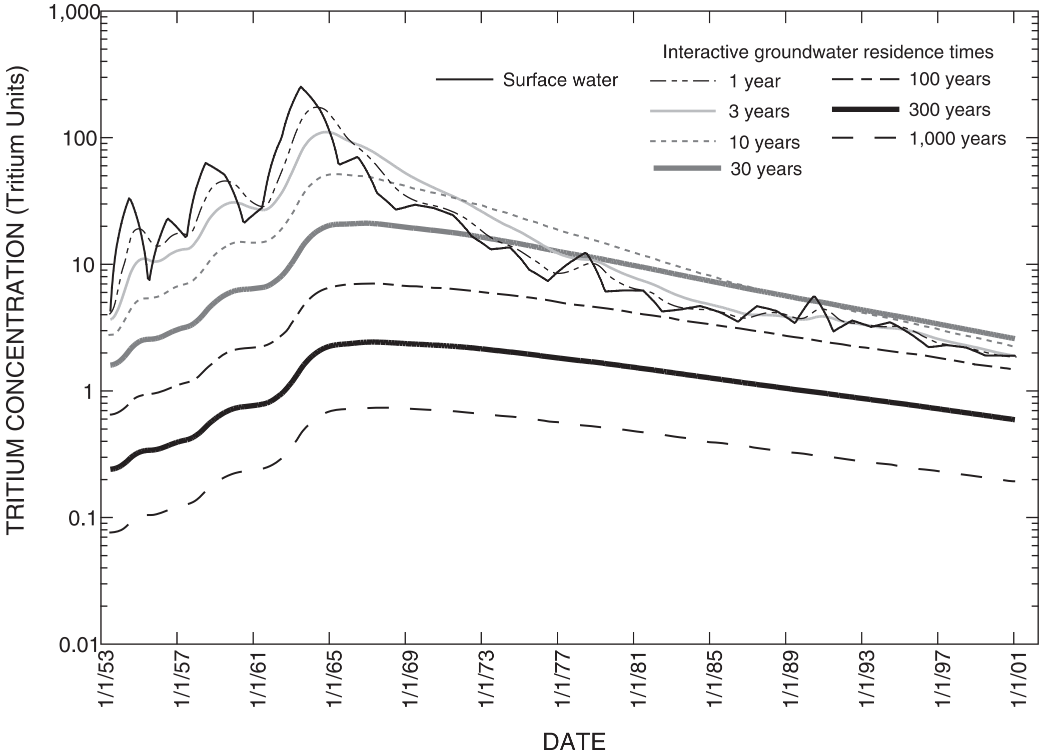

Fig. 6. Modeled tritium concentration in interactive ground water. Results from seven simulations with varying ground-water residence times (1–1000 years) are shown.

residence times associated with ground waters of a specific depth class, there is a tendency for shallow ground waters (<4.5 m) to be associated with younger ages (<100 years), while deeper ground waters (>15-m) are consistently associated with modeled residence times greater than 100 years. The ‘best fit’ simulation to the average ground-water tritium concentration was determined to have a ground-water residence time of 90 years. The best fit simulation is not shown, but the close fit of the simulation with 100 year residence time is apparent in Fig. 7. Dividing the water storage depth in the layer of aquifer with interactive ground water that was determined earlier (3.1 m) by 90 years results in an exchange flux of 0.01 cm d^{-1}. As explained earlier, the values of spatially averaged recharge and discharge fluxes associated with the exchange flux are also 0.01 cm d^{-1}.

We suspected that the residence time of 90 years for shallow interactive ground water might be overestimated due to vertical mixing with deeper, tritium-dead ground water. Independent data were needed to gain further perspective and substantiate a final interpretation. Alternative estimates of ground-water age come from the few analyses of tritium–helium-3 ratios ($^3H/^3He$) that were possible for the sampled wells. There is a practical reason why $^3H/^3He$ may be a better tracer of residence time when available. It provides a better estimate of only the young component of ground water, without being affected by dilution with much older ground water. This is a consequence of using the parent/daughter isotopic ratio as the tracer, because the ratio $^3H/^3He$ is not diluted by upward mixing of tritium-dead ground water. Consequently the residence time is not overestimated. However, the samples are more difficult to collect without corruption and more expensive to analyze. As a consequence, our $^3H/^3He$ measurements were limited to four samples.

The average residence time of shallow ground water indicated by three of the $^3H/^3He$ analyses was

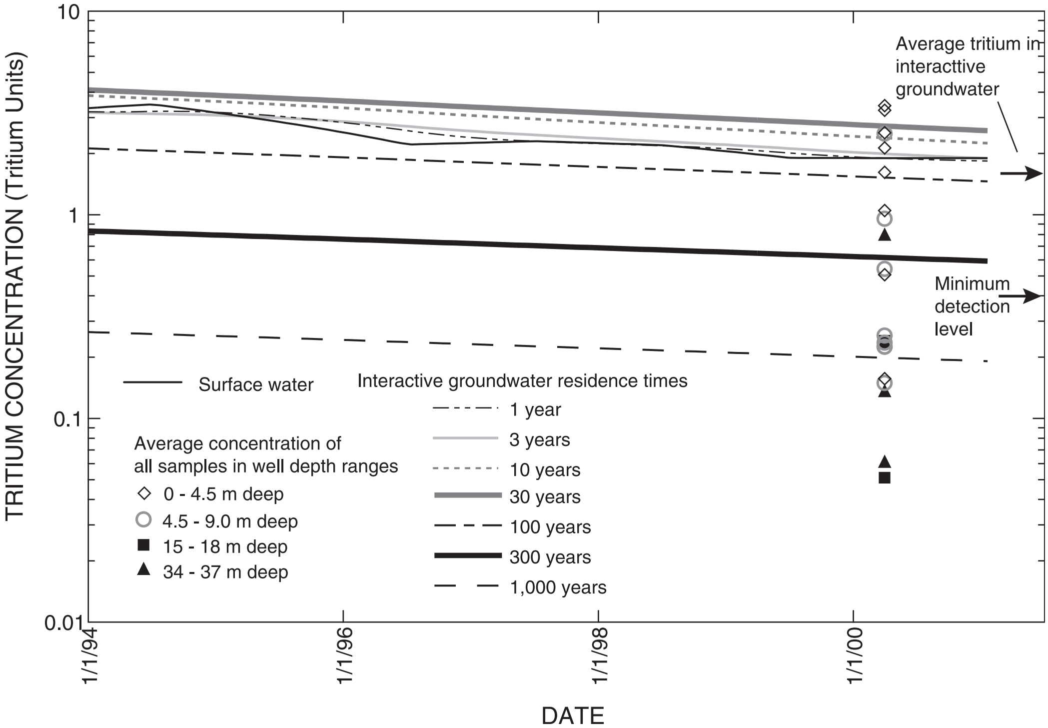

Fig. 7. Tritium modeling results compared with well data from Water Conservation Area 2A, South Florida. ground-water tritium data collected between 1997 and 2001 from each well are plotted together for the date April 2000, and data are further categorized into ranges of well depths with the open symbols representing the shallower depths. The average tritium concentration in interactive ground water (1.5 TU) and the minimum detection level of tritium (0.4 TU) are indicated by arrows along the right *y*-axis. Results from seven simulations are shown with ground-water residence times varying between 1 and 1000 years. A simulation (not shown) with ground-water residence time of 90 years gave the best fit to the average tritium concentration in interactive ground water.

25 years (Table 3). The fourth analysis was from levee site S10C collected from the shallowest well (C) at a depth of 9 m. That water had a much younger age (approximately 2 years), which reflects the much higher driving forces for recharge on the up gradient side of the levee near the S10C site that drives rapid ground-water flow beneath the levee (Harvey et al., 2002). This sample was collected too close to a levee to be representative of interior wetlands and was omitted from the calculation of average residence time.

It is important to emphasize once more that the estimates of recharge and discharge from tritium modeling are considered reliable even though modeling of tritium overestimated ground-water residence time. That is because both ground-water residence time and water storage depth are simultaneously overestimated if vertical mixing occurs (i.e. the total mass of tritium in ground water is unaffected by vertical mixing). Thus, the resulting overestimates of water storage depth and residence time in the interactive ground water will tend compensate one another in the calculation of exchange flux (Eq. (3)), with minimal effect on resulting estimates of recharge and discharge.

Table 3
Ground-water residence times as estimated from analysis of $^{3}H/^{3}He$ ratios

Site	Well depth (m)	Age (years) ± 1 std dev
U3	1.6	21 ± 1
U3	8.0	25 ± 15
F1	2.0	35 ± 1
S10C	9.1	2 ± 2

5. Discussion

Short-term estimates of recharge and discharge from interior areas of the Everglades were recently published (e.g. Krest and Harvey, 2003; Harvey et al., 2004; Harvey et al., 2005), and those fluxes show variability over timescales ranging across from weekly, monthly, seasonal, and interannual timescales. Longer-term (decadal) average estimates of recharge and discharge in interior areas of the wetland would be useful. The present paper addresses that need through application and testing of a coupled model of tritium transport and decay in surface and ground water of WCA-2A in the central Everglades. The form of the model not only permits estimates of recharge and discharge, but, through model sensitivity analyses and comparison with independent estimates of ground-water residence time and horizontal flow rates of ground water and surface water, allows some basic assumptions about spatial variability across the wetland, dominance of vertical compared with horizontal flow in the wetland, etc. to be tested.

Tritium was detectable to a depth of approximately 8 m in the 60-m deep Surficial aquifer beneath the central Everglades in WCA-2A. This contrasts with the results of Price et al. (2003) who found detectable tritium to a depth of 30 m in Everglades National Park. Because of our testing and justifications, we can use the simplified approach of estimating recharge and discharge fluxes for the study of Price et al. using Eq. (3) and compare it with our results from the central Everglades. Since the residence time of shallow ground water (based on $^{3}H/^{3}He$ ratios) was similar in the two studies (approximately 25 years), the greater depth of recharge of young waters in the southern Everglades suggests that recharge and discharge fluxes are probably larger than in the central Everglades, by perhaps a factor of 3 or more. Much of the southern Everglades overlie the highly indurated limestones of the Biscayne aquifer, which is known for its very high hydraulic conductivity (Fish and Stewart, 1991). The north-central Everglades, on the other hand, overlie a sandier unit of the Surficial aquifer, which has a lower hydraulic conductivity (Harvey et al., 2002). Peat thickness, which affects vertical water movement by retarding flow, is generally less in the southern Everglades compared with the north-central Everglades. Greater hydraulic conductivity in the Surficial aquifer and thinner peat support the expectation that recharge and discharge fluxes could be a factor of 3 higher in southern Everglades. However, this preliminary comparison of recharge and discharge fluxes remains a hypothesis at this stage until more estimates of recharge and discharge fluxes in the southern Everglades become available.

An exchange flux of 0.01 cm d^{-1} is an order of magnitude smaller than independent estimates based on modeling naturally occurring, short-lived isotopes of radium (Krest and Harvey, 2003) and Darcy-flux calculations made for the years 1997–2002 (Harvey et al., 2004). There are several possible explanations for this difference. One is uncertainty in assuming that actual tritium concentrations in surface water are equal to the measured tritium in precipitation. If discharge of deep ground water to the canal bottom at the upstream end of the WCA-2A flow system is substantial, then tritium in Everglades surface water may have been overestimated. The potential effect of this error was investigated by reducing the size of the bomb spike in our simulation (by about 50%), which would decrease the ground-water age estimate, from about 90 to 50 years. The effect on the exchange flux estimate is to increase recharge and discharge flux estimates by about a factor of 2, which is not nearly sufficient to explain an order of magnitude difference between the tritium-based estimate and the other independent estimates.

The order of magnitude differences between estimates of recharge and discharge made using long (ground-water tritium modeling) and short (radium modeling in peat porewater and Darcy flux calculations) is probably not the result of bias or error in either method. Instead of great inaccuracies in one approach or the other, we believe that the order of magnitude disagreement between tritium modeling and Darcy flux calculations is more likely the result of comparing techniques that are sensitive to different timescales of interactions between surface water and ground water. The relatively short timescale calculations based on measurements in peat are good at characterizing high fluxes that occur periodically but are short-lived and switch direction frequently (Harvey et al., 2004). Those short-lived fluxes are mainly effective in causing exchange between wetland surface water and peat porewater. Tritium modeling in shallow ground water is insensitive to large and short-lived fluxes that frequently switch direction, because those events only have a minimal effect on tritium in ground water. Instead, tritium modeling is sensitive to the annual and longer term fluctuations associated with factors such as climatic variability, because those longer timescales are effective in exchanging surface water with ground water at depths up to 8 m in the Surficial aquifer. Thus, we believe that it is possible for two independent estimates of recharge and discharge to differ substantially because of different averaging timescales. The correct estimate to use for any particular investigation will depend on the particular problem of interest and its associated timescale. For example, recharge and discharge operating on short timescales could be highly relevant to understanding transport, storage, and re-release of phosphorus from peat porewater. In contrast, longer timescale interactions between surface water and the sand and limestone aquifer could be important in understanding the extent to which relict sea water and its associated dissolved salts are being mobilized deep in the aquifer and discharged to surface water.

5.1. Implications for Everglades water quality

The present study determined the long-term average rate at which the water and solutes presently flowing through the Everglades wetlands are exchanged for water discharging from the sand and limestone aquifer beneath the wetlands. In addition to estimating recharge and discharge as a vertical flux ($0.01\ \mathrm{cm\ d^{-1}}$), the exchange of water can be expressed as a fraction of surface water exchanged per day (0.4%). Due to water management practices and agricultural runoff, surface waters in the central Everglades tend to be contaminated with excessive levels of nutrients, salts, and mercury (Harvey et al., 2002). In the past several decades, the application of best-management practices on farmlands adjacent to the Everglades has helped improve the quality of water flowing into the Everglades. The retention of recharged surface water and its solutes for decades in shallow ground water could have legacy effects for the future, because contaminants that were recently recharged potentially could be returned very slowly to surface waters over a period of decades. Of particular importance could be the recharge of phosphorus over the past few decades, which potentially could be returned to surface water in the next few decades with discharging ground water even if the quality of agricultural runoff continues to improve. The likely timescale at which contaminants now stored in peat porewater and the limestone and sand aquifer are returned to surface water could be decades. Our findings provide a reasonable hydrologic basis for models of that phenomena. One possible result of improved modeling of phosphorus transport is that it could become apparent that rapid initial improvements in water-quality restoration that might be achieved in routing incoming water through treatment wetlands might be difficult to sustain in future years. We stress that these ideas are highly preliminary, and that they need to be thoroughly tested by combining the hydrologic model presented here with biogeochemical data, along with further improvements in components of the coupled surface–sub-surface–biogeochemical model. Only through such improvements can predictions for future water quality be made more reliable.

6. Summary

1. The depth in the shallow, interactive layer of ground water near the top of the Surficial aquifer that exchanges water with surface water on a decadal timescale was estimated in WCA-2A using observations of the depth-distribution of tritium in ground water. That value (3.1 m, after correction by porosity to represent actual water storage) was used as input to a coupled model of transport and decay of tritium in surface water and ground water of Water Conservation Area 2A in the central Everglades. Average ground-water residence time in the model was adjusted to match the average tritium concentration in interactive ground water. Those results were then used to calculate time-averaged recharge and discharge fluxes across the Everglades ground surface, which were on the order of $0.01\ \mathrm{cm\ d^{-1}}$. A check on modeled residence times of interactive ground water was possible by comparison with available measurements of

$^3H/^3He$ isotopic ratios. That comparison demonstrated that vertical mixing of young ground water was occurring with very old (tritium-dead) ground water, which caused both the residence time and depth of interactive ground water to be overestimated. We believe that our resulting estimates long-term average rate of recharge and discharge fluxes are not very sensitive to vertical mixing with tritium-dead water, because of the compensating effect that overestimating both the residence time and depth of shallow interactive ground water has if vertical mixing occurs. As a result, we believe our long-term average estimate of recharge and discharge of 0.1 cm d^{-1} is reliable. For future studies a greater number of $^3H/^3He$ measurements would be preferable of the desirable effect that resulting residence times are relatively insensitive to vertical mixing. Higher analysis costs and frequent failures of $^3H/^3He$ sampling and analysis are not always tolerable, and the present study shows that low-level (0.4 TU Minimum Detection Limit) tritium measurements still have value to investigations of interactions between surface water and ground water.

2. The depth distribution of tritium in ground water of WCA-2A in the central Everglades indicated that relatively recent recharge water had penetrated to a depth of 8 m in the aquifer. This is only approximately 30% of the penetration depth measured by Price et al. (2003) in the southern Everglades within Everglades national Park, which suggests that (since $^3H/^3He$ estimated residence times were similar between the two studies), that recharge and discharge might be as much as three times larger in the southern Everglades compared with the central Everglades. This hypothesis is consistent with what is known about the hydraulic properties of the Surficial aquifer in these two areas of the Everglades (i.e. higher hydraulic conductivity in the Surficial aquifer in many areas of Everglades National Park, particularly on its eastern side).

3. There have been relatively few attempts to develop long-term simulations of contaminant fate and transport in the Everglades that consider ground water–surface water interactions, in part due to a lack of reliable estimates of recharge and discharge. The decadal estimates of recharge and discharge resulting from the present work are complementary to previous short-term estimates of recharge and discharge in WCA-2A. For example, decadal estimates of recharge and discharge are indicative of interactions between surface water and the sand and limestone aquifer, and not just the interactions with peat porewater that are characterized by the short-term estimates in Krest and Harvey (2003); Harvey et al. (2004). Results of this study, when combined with previous investigations, will therefore be useful for guiding future simulations of Everglades water quality.

4. Recharge and discharge fluxes in WCA-2A on the order of 0.01 cm d^{-1} are significant relative to other water balance fluxes such as precipitation evapotranspiration, and surface flow (SFWMD, 1999). One of the most significant side effects of recharge and discharge are its potential influence on solute fate and transport processes in the wetlands. In particular there is concern about the storage of surface-water contaminants, such as phosphorus, in peat and ground water due to recharge and discharge. For example, the effects in the future of recharge of surface-water contaminants today could be evident decades from now, due to the potential for stored contaminants to be returned to the wetland over a period of decades after they were first recharged. More work is needed to understand the potential for such processes to produce historic legacies of contamination in the Everglades long after surface-water inflows from agricultural drainage have been cleaned up.

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